REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE March 30, 1999	3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE

Static and Dynamic Analysis of Structural Frameworks Comprised of Inflatable Arches and Beams

5. FUNDING NUMBERS

DAAH04-95-1-0175

6. AUTHOR(S)

Raymond H. Plaut and Rakesh K. Kapania

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

ARO 33421.14-EG

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This project investigated the behavior of large tent-like structures supported by pressurized arch-shaped tubes. These structures are to be used by the U.S. Army as temporary maintenance shelters for helicopters and airplanes. Similar structures exist, but they are much smaller than those required for this purpose. The aim is to develop a structure that can be separated into lightweight modules which would be easy to transport, deploy, and disassemble.

One part of the research program involved a study of two pressurized arches that lean against each other. This configuration can be an effective component in supporting a fabric shelter. The behavior of single arch-tubes also was analyzed. Deflections, vibrations, and stability were investigated under various types of snow and wind loading conditions. Critical values of the loads were determined. The effects of changing material properties, temperature, and moisture were examined. A finite element model of the entire tent structure was developed.

A numerical optimization study of the supporting arches was conducted. Finally, two physical models of the entire structure were constructed. They were placed in a wind tunnel and tested under various wind speeds and orientations. Then they were tested under simulated snow loads until failure occurred.

14. SUBJECT TERMS

Shelters, maintenance, fabric, transportable, arches

15. NUMBER IF PAGES
4

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

FINAL PROGRESS REPORT

1. **ARO PROPOSAL NUMBER:** 33421-EG
2. **PERIOD COVERED BY REPORT:** 5/1/95 - 12/31/98
3. **TITLE OF PROPOSAL:** Static and Dynamic Analysis of Structural Frameworks Comprised of Inflatable Arches and Beams
4. **CONTRACT OR GRANT NUMBER:** DAAH04-95-1-0175
5. **NAME OF INSTITUTION:** Virginia Polytechnic Institute and State University
6. **AUTHORS OF REPORT:** Raymond H. Plaut and Rakesh K. Kapania
7. **LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP:**

D. M. Carradine and R. H. Plaut, "Experiments on the Response of Arch-Supported Membrane Shelters," International Journal of Space Structures, 1999, to appear.

D. C. Hammerand and R. K. Kapania, "Thermo-viscoelastic Analysis of Composite Plates and Shells Using a Triangular Flat Shell Element," Proceedings of the 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, California, 1998, pp. 515-533.

D. C. Hammerand and R. K. Kapania, "Thermoviscoelastic Analysis of Composite Structures Using a Triangular Flat Shell Element," AIAA Journal, Vol. 37, 1999, pp. 238-247.

D. C. Hammerand and R. K. Kapania, "A Geometrically-Nonlinear Shell Element for Thermo-Rheologically Simple Linear Viscoelastic Laminates," Proceedings of the 40th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 1999, to appear.

R. K. Kapania and J. Li, "A Four-Noded 3D Geometrically Nonlinear Curved Beam Element with Large Displacements/Rotations," Modeling and Simulation Based Engineering, S. N. Atluri and P. E. O'Donoghue, eds., Tech Science Press, 1998, pp. 679-684.

R. K. Kapania and P. Mohan, "Static, Free Vibration and Thermal Analysis of Composite Plates and Shells Using a Flat Triangular Shell Element", Computational Mechanics, Vol. 17, 1996, pp. 343-357.

R. K. Kapania, P. Mohan, and D. C. Hammerand, "Recent Advances in the Development of a Triangular Flat Shell Element," Proceedings of the Fifth Conference on Composites Engineering, 1998, pp. 359-360.

J.-Y. Kim and R. H. Plaut, "Analysis of Tent-Like Structures Supported by Pressurized Fabric Arches," Lightweight Structures in Architecture, Engineering and Construction, Vol. 2, R. Hough and R. Melchers, eds., Lightweight Structures Association of Australia, Randwick, NSW, 1998, pp. 821-829.

P. Mohan and R. K. Kapania, "Updated Lagrangian Formulation of a Flat Triangular Element for Thin Laminated Shells," AIAA Journal, Vol. 36, 1998, pp. 273-282.

P. Mohan and R. K. Kapania, "Geometrically Nonlinear Analysis of Composite Plates and Shells Using a Flat Triangular Shell Element", Proceedings of the 38th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Kissimmee, Florida, 1997, pp. 2347-2361.

P. Mohan and R. K. Kapania, "Analysis of General Shells Under Deformation Dependent Pressure Loads Using a Flat Triangular Shell Element," Proceedings of the 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, California, 1998, pp. 534-541.

S. J. Molloy, R. H. Plaut and J.-Y. Kim, "Behavior of Pair of Leaning Arch-Shells Under Snow and Wind Loads," Journal of Engineering Mechanics, Vol. 125, 1999, to appear.

R. H. Plaut and A. Hou, "Deflections, Vibrations, and Stability of a Pair of Leaning Arches", Journal of Engineering Mechanics, Vol. 124, 1998, pp. 748-753.

R. H. Plaut, J. K. S. Goh, M. Kigudde, and D. C. Hammerand, "Shell Analysis of an Inflatable Arch Subjected to Snow and Wind Loading," International Journal of Solids and Structures, under review. Also to be presented at the 1999 ASME Mechanics and Materials Conference.

S. Suherman and R. H. Plaut, "A Survey of Research on the Behavior and Mechanical Properties of Textile Composites," Report No. CE/VPI-ST 96/08, Department of Civil Engineering, Virginia Tech, July, 1996.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED:

Raymond H. Plaut, Professor

Rakesh K. Kapania, Professor

David M. Carradine, Graduate Student

Julian K. S. Goh, Graduate Student
Daniel C. Hammerand, Graduate Student
Aili Hou, Graduate Student
Martin Kigudde, Graduate Student
Jing Li, Graduate Student
P. Mohan, Graduate Student
Sean J. Molloy, Graduate Student
Surjani Suherman, Graduate Student
Tu Trinh, Graduate Student
Jae-Yeol Kim, Post-Doctoral Fellow

A. Hou, "Analysis of the Deflections, Vibrations, and Stability of Leaning Arches", Master of Science Thesis, September, 1996.

P. Mohan, "Development and Applications of a Flat Triangular Element for Thin Laminated Shells," Ph.D. Dissertation, November, 1997.

D. M. Carradine, "Experiments on the Response of Arch-Supported Membrane Shelters to Snow and Wind Loading," Master of Science Thesis, April, 1998.

D. C. Hammerand, Ph.D. Dissertation, in progress.

J. Li, Ph.D. Dissertation, in progress.

S. J. Molloy, "Finite Element Analysis of a Pair of Leaning Pressurized Arch-Shells Under Snow and Wind Loads," Master of Science Thesis, April, 1998.

J. K. S. Goh, "Analysis of Pressurized Arch-Shells," Master of Science Thesis, December, 1998.

9. REPORT OF INVENTIONS: none

RESEARCH FINDINGS

This project investigated the behavior of large tent-like structures supported by pressurized arch-shaped tubes. These structures are to be used by the U.S. Army as temporary maintenance shelters for helicopters and airplanes. Similar structures exist, but they are much smaller than those required for this purpose. The aim is to develop a structure that can be separated into lightweight modules which would be easy to transport, deploy, and disassemble.

One part of the research program involved a study of leaning arches and shells. Some of the small Army shelters utilize a pair of arch-tubes that lean against each other at the top. This configuration also may be efficient for the framework of the larger structures being envisaged. The effect of various types of loads on such a structural element was analyzed for solid arches and for arch-tubes modeled as shells. It was found that these structural configurations can be designed to be very stable against snow and wind loads.

The behavior of a single arch-tube modeled as a shell was analyzed. Under internal pressure, it was assumed that the cross section was circular and that only in-plane (membrane) stresses were present. An analytical solution for the corresponding initial stresses was obtained for an arbitrary arch centerline shape. Then external loads were applied, and the additional stress resultants included bending and twisting moments. The linear thin-shell theory of Sanders was used to formulate the governing equations, including the initial membrane stresses. The material was linearly elastic, nonhomogeneous, and orthotropic. Approximate solutions were obtained with the Rayleigh-Ritz method. In the examples, the centerline of the arch was a semi-circle, the ends were fixed, and the material was homogeneous and isotropic. Four loads were treated: a symmetric ("full") snow load, an asymmmetric ("half") snow load, a wind load symmetric with respect to the plane of the arch centerline, and a distributed load acting sideways. The resulting deflections were computed and plotted. A computer program for analysis of arch-tubes was given to personnel at the U.S. Army Natick Research, Development and Engineering Center in Massachusetts.

The large deformations of an arch-tube were analyzed numerically using the finite element method with a three-node, flat, triangular element obtained by combining the Discrete Kirchhoff Theory plate bending element and a membrane element similar to the Allman element. The follower effects of the pressure load were included in the formulation. The dynamic analysis capability of the triangular flat shell element was extended to include thermo-viscoelasticity. Linear viscoelastic materials were modeled, resulting in the relaxation moduli being expressed as Prony series. Time-temperature superposition was incorporated to model thermo-rheologically simple materials, for which a change in temperature results in a simple horizontal shifting of the relaxation moduli curves on a log time scale. Hygrothermal loads also were included in the formulation. The results were compared with those obtained using the commercial software package ABAQUS. Then the numerical analysis technique was extended to model the entire tent, i.e., to include a number of arch-tubes and the tent fabric (or skin). At the ends of the tent are a couple of individual leaning arch-tubes, which can be raised to allow a helicopter or airplane to enter or leave the shelter.

Two physical models of the tent were constructed. The dimensions were based on a hangar that has a base of 23 m (75 ft), a height of 15 m (50 ft), and a length of 61 m (200 ft). The scale ratios were 1:50 and 1:100. Each model was placed in a wind tunnel and tested under a range of wind speeds and at several orientations. Large motions occurred when the axis of the structure was perpendicular to the wind direction. Then the models were tested under simulated snow loads until they failed. Deflections were measured during the loading process. The mode of failure depended on the flexibility of the arches.

The material failed when the arches were stiff, whereas the top of the structure inverted when the arches were flexible and the load reached a critical value.

Optimization of the arches with respect to snow and wind loads has been examined. For the shelters, the supporting arches can be manufactured to have almost any desired form (e.g., parabolic or circular), and the optimal form under specified design loading conditions has been determined.

This research grant was carried out in collaboration with the U.S. Army Natick Research, Development and Engineering Center in Massachusetts. Initial contact was with Karen Horak of the Soft Shelters Branch of the Tent Development Team, and continued with Jean Hampel after Ms. Horak left Natick. Professor Plaut visited Natick each of the last four years, and also discussed the project there with Earl Steeves, Arthur Claridge, Tom Godfry, Susan Woodmansee, and two employees of Foster-Miller, Inc. (Paul Chambers and Bob Kardemas). In addition, there was communication with Cheryl Hesselink Stewardson of Natick regarding the material used for these structures.

The status of this project was presented at the 1997 AFOSR/ARO Structural Mechanics Workshop in Myrtle Beach, South Carolina, in September, and by Professor Kapania at the 1997 Spring Meeting of the Virginia Consortium of Engineering and Science Universities (VCES) in Hampton. Also, Professor Plaut attended a forum on Inflatable Structures in Space, held in Houston, Texas, in December, 1996, at which Jean Hampel made a presentation along with representatives from companies that work with Natick on the development of the shelters (Vertigo, FTL/Happold, Fiber Innovations, and Federal Fabrics-Fibers).